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EXPERIMENTAL MEASUREMENTS OF SOIL-MOISTURE HYSTERESIS AND ENTRAPPED AIR

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A moisture-release curve may be determined by removing, stepwise, increments of water and measuring the steady-state soil-moisture suction that develops. A soil-moisture-adsorption curve may be determined in the same way, except that increments of water are allowed to enter the sample. The failure of these two curves to coincide is commonly known as soil-moisture hysteresis (see, for example, figs. 3 to 6).

One mechanism commonly proposed to explain this phenomenon is based on the capillary theory of soil moisture and the heterogeneity of soil pores. Consider, for example, a bottleneck-shaped pore as sketched (*1:1*) in figure 1. As water enters this pore under suction, it fills to a point such that the radius of curvature of the air-water interface corresponds to the suction applied to the water at its source. Consequently, at the given suction and corresponding interface radium *r*, some of the volume in the pore is occupied by air during the wetting cycle. If all openings to the pore contain ducts with radii of *r* or less, these openings should fill with water during the constant-suction period provided for the attainment of steady-state. Such a pore is then said to contain entrapped air. As the wetting increments proceed, the pressure of the entrapped air will rise and slowly diffuse into the fluid phase. In fact, as shown by Bloomsburg and Corey (1), all entrapped air will disappear at zero suction if a sufficient time is allowed. Since a pore such as *1:1* (fig. 1) may be filled with air on the adsorption cycle and filled with water on the desorption cycle, the soil-moisture content during adsorption could be less than the moisture content during desorption.

If such a mechanism does occur, it is reasonable to suppose that the discrepancy in volume of moisture between the wetting and drying curves will be correlated with the volume of entrapped air in the sample, that is the volume of entrapped air will be greater on the wetting cycle and less on the drying cycle. Moreover, one would expect the entrapped air to be less than the water volume discrepancy which occurs between the wetting and drying curves. Some of the hourglass-shaped pores could completely fill with water following a sharp decrease in suction simply because the flow path around to one or more of the pore's vents was too slow to allow plugging with water before the air escaped.

The preceding discussion is based on the concepts put forth in the pioneering work of Haines (7), whose investigations have provided a basis for several theoretical studies of moisture hysteresis in porous materials [see, for example, Miller and Miller (8) and Poulovassilis (9)].[2]

On the other hand, Chahal (2, 4) has studied the effect of entrapped air on the temperature dependence of soil-moisture suction. This temperature dependence is generally greater than can be accounted for by the temperature dependence of the capillary theory resulting from the surface tension of water. In order to explain the greater temperature coefficient on a basis of entrapped air, Chahal suggested

[1] Contribution from the Snake River Conservation Research Center, Soil and Water Conservation Research Division, Agricultural Research Service, Kimberly, Idaho, in cooperation with the Department of Water Science and Engineering, University of California, Davis, California. The author is grateful for the many helpful comments of Jim Davidson, Oklahoma State University.

[2] Complete reviews of the literature concerning soil moisture hysteresis may be found in the recent dissertations prepared by J. M. Davidson (University of California, Davis, 1965) and G. C. Topp (University of Wisconsin, 1964). A review of literature concerning entrapped air has been included in a report prepared by Bloomsburg and Corey (1).

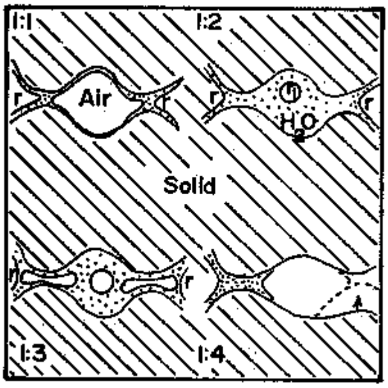

FIG. 1. Possible configurations of trapped air in bottleneck-type soil pores.

that the volume of entrapped air increased during the initial stages of the soil moisture desorption cycle.

In view of these two apparently contradictory concepts, it appeared worthwhile to make some measurements of entrapped air during the adsorption and desorption cycles of soil moisture.

EXPERIMENT

The simultaneous measurements of hysteresis and volume of entrapped air were made in the apparatus diagrammed in figure 2. A sand, loam, or clay soil sample was held in a lucite chamber 7 inches in diameter. The sample volume, approximately 1025 ml., was separated from the water reservoir on the bottom by a fritted glass plate. The moisture content in the sample was controlled by the vacuum pressure applied to the outflow tube. The outflow tube was a burette used to measure the volumes of water leaving or entering the soil sample. The soil was packed into the chamber in an air-dried state, then wet up and run through 6 to 10 wetting and drying cycles to allow it to stabilize. Experimental observations were started by applying a given vacuum to the outflow tube. When the water level in the outflow tube became constant and when the tensiometer in the soil became constant, the amount of water inflow or outflow was noted. This generally occurred two or three days after the vacuum setting was made. At this time the outflow tube was clamped off, the 500-ml volumetric flask was clamped off, and a pressure of approximately 50 cm. of water above atmospheric was applied to the soil sample. This was allowed to equilibrate for about 10 minutes before the pressure was relaxed into the 500-ml. flask. The change of air pressure in the system was observed with the water manometer. This pressure increase and relaxation procedure was carried out at least five times, and the soil's air volume calculated for each test.

The soil sample was then vented to the atmosphere, the outflow line was opened, and a new vacuum setting was made on the outflow tube. Thus it was possible to compare the change in air volume with the change in moisture volume as the hysteresis loop was followed.

The temperature throughout the experiment was held at 25° ± 1° C. During the air-volume measurements, special care was taken that ambient temperatures around the soil sample and the volumetric flask did not change more than 0.03° C. Volume measurements of soil air were somewhat dependent upon both the magnitude of the initial pressure increase and the length of time following pressure changes at which the water manometer was read. When the pressure was initially raised to 50 cm. of water above atmospheric, the pressure on the water manometer showed a slow decrease, evidently due to the combined effects of the solution of air, its diffusion into the voids of entrapped air, and the compression of entrapped bubbles. Then, when the system was relaxed into the 500-ml. volumetric the water manometer registered a slow increase in pressure for several minutes as these effects reversed.

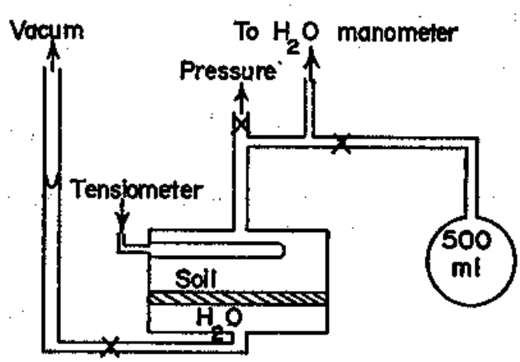

FIG. 2. Apparatus used to measure soil-moisture inflow and outflow rates and hysteresis loops of moisture content and air volume as function of suction.

Reproducible measurements were obtained by waiting 2 minutes after the relaxation of pressure into the 500-ml. flask before taking a pressure reading from the water manometer. The mean of five relaxation pressure changes was used to determine each volume. The maximum variations about the mean were ±4 ml., with most observations being within ±2 ml. of the mean.

CALCULATIONS

The volume of air in the sample which communicates with the atmosphere may be calculated from the perfect gas law, starting with the basic relations

$$P_1V = n_1 RT \qquad (1)$$

$$P_2 (V + 520 + \Delta v) = (n_1 + n_2) RT \qquad (2)$$

and

$$520 P_0 = n_2 RT \qquad (3)$$

where P_1 is the ambient pressure on the soil after the 50-cm. increment was applied; P_2, the pressure after relaxation into the 500-ml. flask; V, the volume of unentrapped soil air at P_1; 520, the volume of the flask and its connecting lines; Δv, the change in volume of the entrapped air as the pressure goes from P_1 to P_2; n_1, the mass of unentrapped gas in the soil at P_1; n_2, the mass of gas in the flask system under atmosphere pressure P_0; R, the universal gas constant, and T, the absolute temperature. Equation (2) assumes there is a negligible exchange of gas between the entrapped and unentrapped air during the 2-minute relaxation period.

Solving equations (*1*), (*2*), and (*3*) for V gives

$$V = \frac{520 (P_2 - P_0) + P_2\Delta v}{P_1 - P_2} \qquad (4)$$

The quantity Δv can be written in terms of the perfect gas law through use of the expression

$$P' = P + \tau + \frac{2\sigma}{r_1} \qquad (5)$$

where P' is the pressure in the entrapped air bubble; P, the external ambient pressure; τ, the soil moisture suction; σ, the surface tension of the air-water interface; and r_1, the effective radius of the entrapped air bubble. The solution of Δv through use of equations of the type (*1*) and (*5*) requires a value for r_1, which is not available. Thus, as a first approximation, one may suppose $\Delta v \simeq$ zero and write equation (*4*) as

$$V = \frac{520\, p}{\Delta p} \qquad (6)$$

where p is the pressure registered by the water manometer after relaxation and Δp the change in pressure caused by the relaxation. Because $P_1 > P_2 > P_0$, it follows that $\Delta v <$ zero, thus equation (*6*) tends to overestimate the true value of V. It follows from equation (*8*) that this will cause the volume of entrapped air to be underestimated.[3]

The total volume of the sample was related to the volumes of its components as

$$A = v + \theta + B + V \qquad (7)$$

where A is the total sample volume; v, the volume of trapped air; θ, the volume of the soil's moisture; and B, the volume of the soil's solid phase.

To arrive at a numerical value for the trapped air, the volumes of the sample's components as shown in equation (*7*) all had to be measured at the termination of the experiment. Since each of these measurements had a potential error of 5 or 10 ml., it was only possible to calculate absolute trapped air volumes within a certainty of around ±30 ml. Since this potential error is much greater than the ±4-ml. variation involved in measuring changes in air volume with equation (*6*) and changes in moisture content with the burette, equation (*8*) was utilized

$$v + \varepsilon = A - B - V - \theta \qquad (8)$$

where ε is the unknown but constant experimental error arising from the individual measurements of the volume of soil moisture, soil solids, and the untrapped air at the end of the experiment.

RESULTS

Experimental values of entrapped air plus ε are plotted in figures 3–6 along with the si-

[3] It should be noted that equation (*6*) is not Boyle's law, though Boyle's law has been applied to the analysis of entrapped air by Gupta and Swartzendruber (6) and Chahal (4).

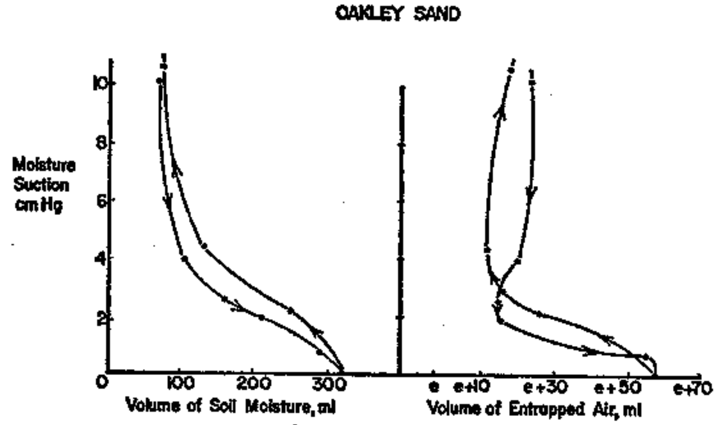

FIG. 3. Simultaneous measurements of soil-moisture hysteresis and entrapped air.

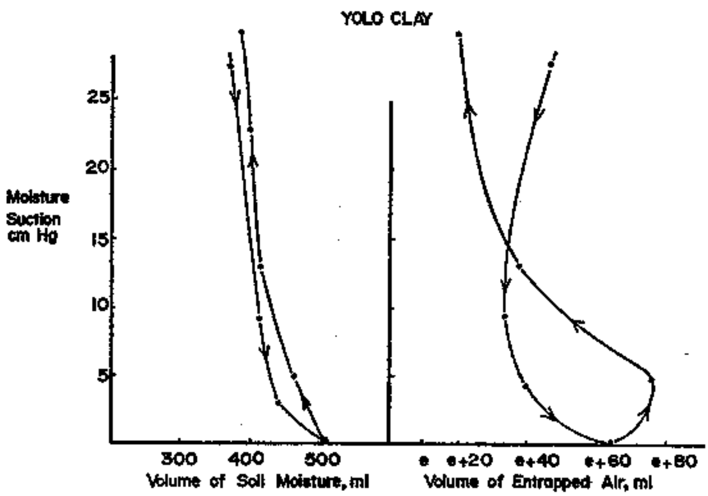

FIG. 4. Simultaneous measurements of soil-moisture hysteresis and entrapped air.

multaneously measured soil moisture hysteresis loops. ε is, of course, a constant for each soil. By plotting the data in this manner, the individual trapped air observations associated with the hysteresis loop have minimum experimental errors with respect to each other. While the shape of the curves may be biased, particularly at the high moisture contents, by the assumption Δv = zero, the author feels that a difference of 5 ml. or more between the curves at any given suction may be considered a significant difference in entrapped air.

Figure 3 shows the results obtained with an Oakley sand sample from the same bulk stock as that used by Davidson.[4] Figure 4 shows the results from a sample of Yolo clay kindly supplied by Jim Vomocil of the University of California at Davis. Figure 5 shows the results on a sample of Columbia soil where the moisture change was allowed to take place in five steps. Figure 6 shows the results with the same sample of Columbia loam but with the moisture change taking place in three steps. Short scanning loops are also shown in figure 6.

In agreement with the results published by

[4] J. M. Davidson, Ph.D. dissertation, University of California, Davis, 1965.

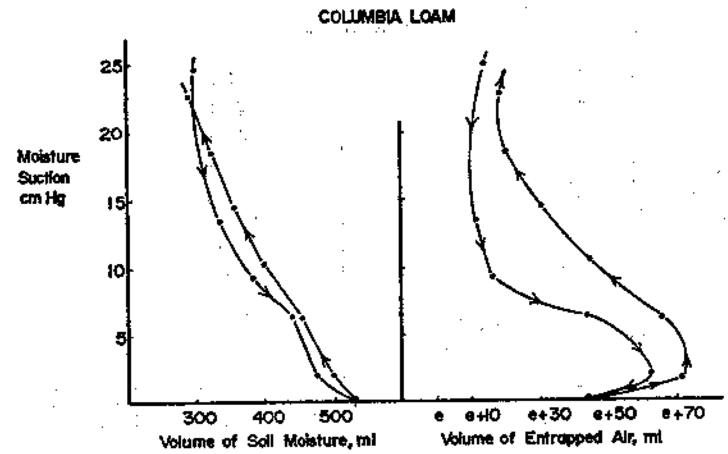

FIG. 5. Simultaneous measurements of soil-moisture hysteresis and entrapped air.

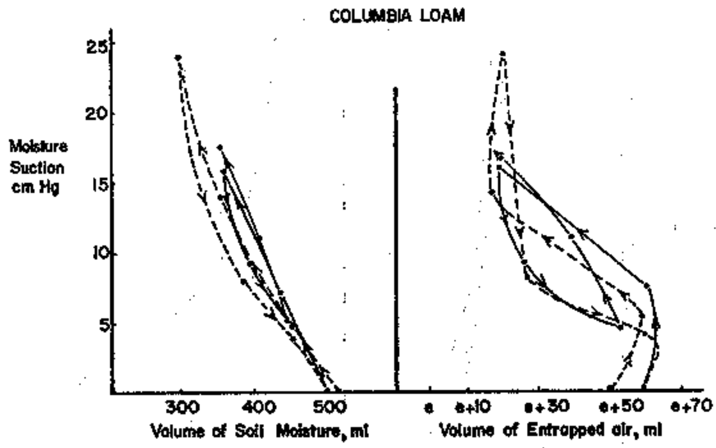

FIG. 6. Simultaneous measurements of soil-moisture hysteresis and entrapped air: (*dashed curves*) a three-step cycle, and (*solid lines*) scanning loops.

Davidson *et al.* (5), the shape of the hysteresis curves are rate-dependent (see fig. 5 and 6). More moisture was held by the loam sample at zero suction when inflow rates are slow, that is when more steps are used to cover the suction range. Judging from the associated trapped-air curves, the increase in moisture content at zero suction was associated with a smaller volume of trapped air.

As described earlier, in this paper, the "bottleneck" hysteresis theory implies that the volume of trapped air should be least on the moisture-desorption cycle. Data in figures 3 through 6, however, show that this occurred only with the sand sample at suctions greater than 3 cm. Hg and with the clay sample when the suction was greater than 16 cm. Hg. In direct contrast to this hypothesis, all three soils had greatest volumes of trapped air during initial stages of moisture desorption. These data tend to support the requirement of an initial increase of trapped air during desorption, as required by the analysis of Chahal (1). This cannot, however, be taken as a final verification of Chahal's theory, since there is considerable latitude in evaluating the unknown parameters in his temperature-dependent equation.

One might present a number of postulates to explain the increase of trapped air on desorption. Suppose that, upon the wetting cycle, the condition showed as *1:1* in figure 1 developed. As inflow continued, a bubble would form (*1:2*, fig. 1). As the soil-moisture suction decreased, the pressure in this bubble would rise in accordance with equation (*5*). The rise in P' would cause a partial-pressure gradient and, consequently, a diffusion of gas between the trapped and unentrapped air. Whether this diffusion transfer was significant would depend upon the thickness of the water film entrapping the air bubbles (1). If this transfer were significant, the mass of air in the entrapped air bubbles would decrease during inflow until the water films became prohibitively thick. On the other hand, when outflow takes place, the nucleation of air bubbles could be such that the entrapping water films would be thinner. This would result in a greater inward gas diffusion and, consequently, more trapped air during desorption. If such a system does operate in the soil, for a given moisture content, say θ_1, the air bubbles would occupy different volumes during wetting and drying as shown in *1:2* (wetting) and *1:3* (drying) figure 1. For such an idealized pore, the effective radius should be greater for the larger volume of trapped air. This suggests that the suctions predicted from capillary theory should be less on the desorption cycle than that on the adsorption cycle, which is not in accord with experimental observations. On the other hand, in figure 1 the average moisture-film thickness in *1:3* would be less than the average film thickness in *1:2* in this idealized pore. If the film thickness and solid-liquid interface are important in determining the moisture suction, it could be possible for the suction to be higher in the case of *1:3,* even though it contains the same amount of moisture as the pore in *1:2*.

A second and perhaps more likely postulate can be based on the fact that the soil matrix is not rigid. As water flows into the soil on the wetting cycle, pockets of air may be enclosed by the wetting film *1:1* (fig. 1). As the moisture content increases, the general tendency would be for a separation of the mineral particles by the wetting moisture-film (that is, swelling). Thus, average pore diameters in the soil could be expected to reach a maximum as saturation is approached. On the other hand, during the desorption cycle, as the moisture leaves the tendency would be to draw the mineral particles closer together, which would result in a decreasing effective pore-size distribution. It might be that some of the larger pores would empty initially, but as further decreases in moisture content occurred, a shrinkage of the neck portions of some of the emptied pores might result from particle reorientation, as diagrammed as *1:4* in figure 1. A water meniscus could then reform across these necks, trapping the additional air noted during the desorption cycle. A smaller effective pore-size distribution during outflow would also explain the higher suctions on the desorption cycle at any given moisture content. Using the gamma ray technique, Davidson[5] has shown that there are changes in bulk density associated with wetting and drying of the Columbia silt loam. However, he found very little density change associated with the hysteresis loops on Oakley sand.

No matter what the mechanism of air entrapment, the data presented here in conjunction with that of Topp and Miller (10), and Davidson *et al.* (5) suggest that there is not yet a quantitative theory which fully describes the soil moisture hysteresis phenomenon. In view of the fact that the entrapped air volumes do not follow the pattern implied by the "bottleneck or Haines jump" concept, and in view of the fact that the hysteresis loops are dependent upon rate of wetting and drying, existing mathematical treatments and even some of our qualitative concepts must undergo additional evolution before they can give accurate descriptions of the phenomenon. Possibly the data and experimental techniques presented here will be of some help.

SUMMARY

The relation between moisture hysteresis and changes in the volume of entrapped air were experimentally measured on a sand, a loam, and a clay soil. These measurements showed that in the low moisture-suction range there is more entrapped air during desorption than during adsorption. The results are in general disagreement with the relation implied by the classical "bottleneck" pore theory. They are, however, in agreement with parts of the hypotheses proposed by Chahal when at-

[5] *Ibid.*

tempting to explain the analogously high temperature dependence of soil-moisture suction.

Two possible explanations are presented to suggest why the soil might have a larger volume of trapped air during the initial stages of desorption. These explanations are based on the nonrigid nature of the soil matrix and the possibility of a significant diffusion of gas between the atmosphere and trapped air pockets.

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